INTEGRATED NARROW-LINE TUNABLE OPTICAL PARAMETRIC OSCILLATOR

CROSS-REFERENCE TO RELATED APPLICATIONS

[0001] Not Applicable

STATEMENT RE: FEDERALLY SPONSORED RESEARCH/DEVELOPMENT

[0002] Not Applicable

BACKGROUND OF THE INVENTION

[0003] Optical ~~P~~parametric ~~O~~oscillation is a nonlinear process that converts a single input laser beam or a pump radiation source into two lower energy-beams known as the signal beam and the idler beam. The wavelengths/frequencies of the ~~pump~~ various beams λ_{pump}/f_{pump}, $\lambda_{signal}/f_{signal}$, and $\lambda_{idler}/f_{idler}$ must satisfy:

$$\frac{1}{\lambda_{pump}} = \frac{1}{\lambda_{signal}} + \frac{1}{\lambda_{idler}} \qquad (1), \text{~~or equivalently~~}$$

or equivalently

$$\omega_{pump} = \omega_{signal} + \omega_{idler} \qquad (2)$$

Ideally, energy is conserved since the sum of photon energies of the signal beam and the idler beam is equal to the photon energy of the pump beam, ~~(The~~ that is, the energy of a photon is proportional to the frequency thereof~~)~~. There is no explicit requirement for the optical parametric oscillation to have the wavelengths of resulting beams related directly to the wavelength of the pump beam as long as the resulting beams satisfy the equations (1) and (2). Therefore, it is possible to implement a laser capable of being continuously tuned over a wide range of wavelengths by adjustment of the optical parametric oscillation only. ~~In other words, the whole process~~ The optical parametric oscillation can be tuned to create ~~in effect~~ a multicolor laser system, - by changing the ~~refractive index~~ grating spacing of the nonlinear crystal, for example, which can be achieved by controlling temperature of the nonlinear crystal, or accomplished by rotating the crystal relative to the incident light beam.

[0004] Figure 1 shows a schematic setup of ~~an~~ a typical optical parameter oscillator. As shown, a ~~powerful radiation of a~~ pump beam is generated from a pump laser 10 to propagate through an optically-nonlinear crystal 12 placed in an optical resonator comprised of a pair of mirrors 14. While traveling through the optically-nonlinear crystal 12, a small portion of the pump beam is converted into a signal ~~wave~~ beam and an idler ~~wave~~ beam. The signal ~~wave~~ beam and/or the idler ~~wave~~ beam are fed back by the mirrors 14I and 14O of the optical resonator. ~~For each propagation through~~ When the pump beam is coupled into the nonlinear optical crystal 12, the signal ~~wave~~ beam and/~~or~~ ~~the~~ idler ~~wave~~ ~~are amplified by a certain factor~~ beam may be generated depending on the intensity of the pump beam and the reflectivities of the mirrors 14. Each optical parametric oscillator has a characteristic pump-intensity threshold. At and above the threshold, the amplification of the signal and idler ~~waves~~ beams compensates the resonator roundtrip loss caused by residual mirror transmission, crystal absorption, scattering, etc. ~~Only~~ ~~if~~ If the optical parametric oscillator is pumped above the threshold, a significant amount of pump ~~radiation~~ beam is converted into signal and idler radiation. In practice, the input mirror 14I is designed with maximum reflectivity for the signal beam and/~~or~~ idler beam, and the output mirror 14O determines whether the optical parametric oscillator is ~~a~~ singly- or doubly-resonant. That is, the output mirror 14O determines ~~either one of or both~~ the proportions of the signal ~~wave~~ beam and the idler ~~wave~~ beam to be fed back to the nonlinear crystal ~~and~~ 12 and resonated in the optical resonator.

[0005] Applications of optical parametric oscillation include light detection and ranging (LIDAR), high-resolution spectroscopy, medical research, environmental monitoring, display technology and precision-frequency metrology. In ~~the~~ coherent-detection applications of LADAR, vibrometry, and free-space optical (FSO) communication, a tunable, narrow-line, high-power source with wavelength (λ) of 1.5 microns is required. For example, coherent LADAR could require a source of about 10 Watts to about 100 Watts at a wavelength (λ) of about 1.54 microns with tunability of 1 nanometer over a 50 micro-second chirp, and linewidth as narrow as 50 ~~K~~kHz. It is likely that LADAR will rely on gas lasers to achieve these narrow linewidths in the near term. Similarly, airborne, free-space-optical communications will require a wavelength of about 1.5 ~~micrometers~~ microns with some ~~tenability~~ tunability within the C-band and the linewidths of 100 ~~K~~kHz in a coherent-detection mode. ~~Air-borne~~ Airborne free-space-optical communication will rely on existing telecommunication components in the near term, such as a 1

micro-Watt laser diode, followed in series by erbium-doped fiber amplifiers (EDFA's) to achieve ~~the~~ powers of ~~1-5~~ 10 Watt. Polarization-maintaining erbium-doped fiber amplifiers are expensive; ~~and~~ moreover, high-end erbium-doped fiber amplifiers may provide no more than ~~several~~ tens of Watts of power each. As the airborne free-space-optical range requirements increase, it is a challenge for sources to provide more power without sacrificing linewidth.

[0006] ~~Research and development of applying nonlinear~~ Nonlinear optics have been applied to the above missions ~~have been commenced~~ for a number of years. For example, ~~the~~ pumping optical parameter oscillators (OPO's) with Nd:YAG laser sources ~~are~~ is a highly reliable ~~to~~ approach for tunable, high-power sources. Materials used ~~as the pumping~~ to pump optical parameter oscillators include periodically-poled lithium niobate ($LiNbO_3$ or PPLN). ~~With such material, a power of tens~~ Tens of Watts at a wavelength of about 1.064 micrometers can be pumped into PPLN prior to approaching ~~the~~ its laser-damage threshold ~~thereof~~. However, these types of optical parametric oscillators tend to have fairly broad linewidth.

[0007] Narrow-linewidth operation (~~about~~ $\Delta\lambda\sim$0.02 nanometer) of optical parametric oscillator has been achieved using a Littrow configuration disclosed in literatures such as "Littrow Configuration Tunable External Cavity Diode Laser with Fixed Output Beam" by C.J. Hawthorn, K.P. Weber, R.E. Scholten in Review of Scientific Instrement Instrument, Vol. 72(12) pp4477-4479, Dec. 2001. Bosenberg et al. have also demonstrated a single-crystal optical parametric oscillator based on $KTiOPO_4$ (KTP), a grating, and a tuning mirror. These disclosures indicated that fine tuning of one mirror provides a wavelength-selection mechanism, in which the optical parametric oscillator can be selectively seeded for a given narrow line. However, in these optical parametric oscillators, the resonator ~~(the mirrors)~~, the grating, and the nonlinear crystal are separate devices such that precise alignment is highly demanded, but it is laborious and time consuming. Further, ~~the~~ this conventional ~~tuning mirror still has the optical limit in tuning the light beam for achieving a fine and agile steering.~~ approach involves mechanically tuning the mirror.

BRIEF SUMMARY OF THE INVENTION

[0008] The present invention provides an integrated optical parametric oscillator for converting a pump ~~radiation~~ beam into a signal ~~wave~~ beam and an idler wave beam, ~~and to provide~~ while providing a fine tuning of the signal ~~wave~~ beam. The integrated tunable optical

parametric oscillator comprises ~~an incident plane,~~ an optical parametric oscillation region, a grating ~~plane, an emerging plane, a reflecting plane~~, and a fine-steering region in one monolithic crystal. The incident ~~plane~~ face is anti-reflective to the pump ~~radiation~~ beam and reflective to the signal ~~wave~~ beam and the idler ~~wave~~ beam, such that the pump ~~radiation~~ beam can ~~transmit through the incident plane.~~ be coupled into the crystal. After ~~transmitting through the incident~~ plane coupling into the crystal, the pump ~~radiation~~ beam is converted into the signal ~~wave~~ beam and the idler ~~wave~~ beam by the optical parametric oscillation region in ~~front of the incident plane.~~ a first section of the crystal. The signal ~~wave~~ beam and ~~the~~ idler beam ~~wave~~ are then incident on the ~~grating plane~~ ~~.~~holographic grating. ~~A portion~~ Portions of the signal and idler ~~waves diffracted~~ beams are specularly reflected by the grating ~~plane~~ towards the ~~emerging~~ plane output face, ~~and the other portion~~ while some of the signal and idler ~~waves is reflected~~ beams are diffracted towards the ~~reflecting plane by the grating plane.~~ fine-tuning region. The ~~emerging plane~~ output face is anti-reflective to the signal ~~wave~~ beam and reflective to the pump ~~radiation~~ beam and the idler ~~wave~~ beam. Therefore, the signal ~~wave diffracted by the grating plane~~ beam is allowed to ~~emerge via the emerging~~ plane couple out of the crystal, while the idler ~~wave diffracted by the grating plane~~ beam is reflected ~~by the emerging plane~~ back towards the grating ~~plane or the incident plane~~. The reflecting face of the fine-tuning region ~~plane~~ is reflective to the pump ~~radiation~~ beam, the signal ~~wave~~ beam and the idler ~~wave~~ beam. ~~;and therefore, the other portion of the signal and idler waves reflected from the grating plane is reflected back to the grating plane.~~ The fine-steering region is formed between ~~the reflecting plane~~ its reflecting face and the grating ~~plane~~. The fine-steering region ~~is operative to change the optical path of~~ produces an active index gradient to steer the signal ~~wave~~ beam ~~incident onto~~ to and from the grating ~~plane~~. As the signal ~~wave~~ beam is ~~incident~~ steered back on the grating ~~plane~~ with a ~~different incident~~ selected angle, the signal ~~wave~~ beam is ~~diffracted~~ seeded by the grating ~~plane with a different~~ for a particular wavelength. Thereby, the ~~tenability~~ tunability is obtained.

[0009] Preferably, the ~~incident plane~~ input face, the optical-parametric-oscillation region, the grating ~~plane~~, the ~~emerging plane~~ output face, ~~the reflecting plane~~ and the fine-steering region are integrated on a single slab of a nonlinear optical bulk material. The nonlinear optical bulk material choices include~~s~~ lithium niobate crystal. The optical-parametric-oscillation region includes a part of the nonlinear optical bulk material being periodically poled, while the fine-steering region includes a part of the nonlinear optical bulk material and a ~~pair~~ pattern of

electrodes deposited on two opposing surfaces ~~of~~ thereof. That is, the fine-steering region includes a part of the nonlinear optical bulk material subjected to a~~n~~ dynamic electric field. In one embodiment, the pump ~~radiation~~ beam has a wavelength of about 1.064 micrometers, the signal ~~wave~~ beam has a wavelength of about 1.54 micrometers, and the idler wave has a wavelength of about 3.442 micrometers. Alternatively, the pump ~~radiation~~ beam has a wavelength of about 1.064 micrometers, the idler ~~wave~~ beam has a wavelength of about 1.54 micrometers, and the signal ~~wave~~ beam has a wavelength of about 3.442 micrometers. The choice of grating ~~plane~~ technique includes a holographic grating with about 200 grooves/mm to about 500 grooves/mm, for example.

[0010] The present invention also provides an integrated optical parametric oscillator, comprising a nonlinear optical bulk material, which includes a locally periodically-poled region and a fine-steering region subjected to an electric field. The nonlinear optical bulk material includes ~~a~~ lithium niobate, and the locally periodically-poled region has a length of about 30 mm, for example. The nonlinear optical bulk material further comprises a plurality of exterior coated planes forming a resonator of a wave at predetermined wavelength.

[0011] The present invention further provides a tunable, narrow-line laser system comprising a pump ~~radiation~~ beam source and an integrated parametric oscillator. The pump ~~radiation~~ beam source is operative to generate a pump ~~radiation~~ beam. The integrated optical parametric oscillator comprises a nonlinear optical bulk crystal. The nonlinear optical bulk crystal ~~countered~~ is contoured with an ~~incident plane~~ input face, a grating ~~plane~~, an ~~emerging plane~~ output face and a reflecting plane. Between the ~~incident plane~~ input face and the grating ~~plane~~, an optical parametric oscillation region is formed. Between the grating ~~plane~~ and the reflecting plane, a fine-steering region is formed. The ~~incident plane~~ input face is anti-reflective to the pump ~~radiation~~ beam, ~~which~~ so that the pump ~~radiation~~ beam can enter the nonlinear optical bulk crystal by transmitting through the ~~incident plane~~ input face. The optical parametric oscillation region is operative to convert the pump ~~radiation~~ beam into a signal ~~wave~~ beam and an idler ~~wave~~ beam. ~~A portion~~ Portions of the signal and idler ~~waves~~ ~~is diffracted~~ beams are reflected towards the ~~emerging plane~~ output face by the grating ~~plane~~, while the other portions of the signal and idler ~~waves is~~ beams are ~~reflected~~ diffracted from the grating ~~plane~~ towards the reflecting plane. The ~~emerging plane~~ output face allows the ~~diffracted~~ narrow-line signal ~~wave~~ beam to ~~transmit through~~ be coupled out~~,~~ while ~~reflects~~ reflecting the diffracted idler ~~wave~~ beam

back to the grating ~~plane~~ or the ~~incident plane~~ input face. Meanwhile, the signal and idler ~~waves~~ beam ~~reflected from~~ diffracted by the grating ~~plane being~~ are reflected from the reflecting plane through the fine-steering region back to the grating ~~plane~~. ~~However, as a~~ The fine-steering region is formed between the reflecting plane and the grating ~~plane~~. An optical path difference of the reflected portion of the signal and idler ~~waves~~ beams is generated. Therefore, the incident angle of the reflective portion of the signal wave is changed~~; thus provides wavelength tenability~~, and wavelength tunability is obtained.

[0012] Preferably, the pump ~~radiation~~ beam source includes a Nd:YAG laser operative to generate a pump ~~radiation~~ beam with a wavelength of about 1.064 micrometers. The nonlinear optical bulk crystal includes a lithium niobate crystal. The optical parametric oscillation region includes a periodically-poled region of the nonlinear optical bulk crystal with a length of about 30 mm. The optical-parametric-oscillation region is operative to convert the pump ~~radiation~~ beam into the signal ~~wave~~ beam with a wavelength of about 1.54 μm and the idler ~~wave~~ beam with a wavelength of about 3.442 μm. Or alternatively, the optical-parametric-oscillation region is operative to convert the pump ~~radiation~~ beam into the signal ~~wave~~ beam with a wavelength of about 3.442 μm and the idler ~~wave~~ beam with a wavelength of about 1.54 μm. The fine-steering region includes a region of the nonlinear optical bulk crystal subjected to ~~an~~ dynamic electric field. Preferably, the ~~incident plane~~ input face, the grating ~~plane~~, ~~emerging plane~~ output face, and the reflecting plane are all reflective to the idler ~~wave~~ beam and arranged as a resonator of the idler ~~wave~~ beam. When the nonlinear optical bulk crystal is fabricated from zinc selenium (ZnSe), the spectral range between 1 micron and 5 microns, or 8 microns and 12 microns, can be facilitated.

BRIEF DESCRIPTION OF THE DRAWINGS

[0013] These, as well as other features of the present invention, will become apparent upon reference to the drawings wherein:

[0014] Figure 1 shows a conventional optical parametric oscillator;

[0015] Figure 2 shows a schematic drawing of an integrated optical parametric oscillator; and

[0016] Figure 3 shows the optical path of the pump wave, the signal ~~wave~~ beam and the idler ~~wave~~ beam within the integrated optical parametric oscillator.

DETAILED DESCRIPTION OF THE INVENTION

[0017] The present invention provides an optical parametric oscillator which integrates all critical components of the above Littrow configuration into a single slab of nonlinear optical material. As shown in Figure 2, the optical parametric oscillator includes a single slab of nonlinear optical bulk material 20, preferably a lithium-niobate crystal ($LiNbO_3$). By locally periodically poling the nonlinear optical bulk material 20 ~~periodically~~, a part of the nonlinear optical bulk material 20 ~~is processed~~ functions as an optical-parametric-oscillation region 22 operative to convert a pump ~~radiation~~ beam λ_p into waves with wavelengths longer than that of the pump ~~radiation~~ beam λ_p. As mentioned above, the converted waves include one signal ~~wave~~ beam λ_s and one idler ~~wave~~ beam λ_i. For example, when the wavelength of the pump ~~radiation~~ beam λ_p is about 1.064 microns, the wavelengths of the signal and idler, ~~wave~~ beams λ_s and λ_i, converted by the optical-parametric-oscillation region 22 are about 1.54 microns and 3.442 microns respectively. Preferably, the optical-parametric-oscillation region 22 has a length of about 30 mm. In addition to the optical-parametric-oscillation region 22, the nonlinear optical bulk material 20 further includes a fast, ultra-fine-steering region 24, which is formed by depositing a pattern of electrodes 26 on both sides ~~of another part~~ of the nonlinear optical bulk material 20. By applying an electric field across the steering region 24 via the grid of electrodes 26, the refractive index of the fine-steering region 24 is modulated, such that an optical path difference is induced to an optical wave propagating through the steering region 24. The optical path difference of the optical wave is proportional to the modulation of refractive index as:

$$\mathrm{OPD}(x, y) = nL(x) \qquad (3),$$

where OPD(x, y) is the optical path difference ~~along an x-axis, which is the propagating direction in this embodiment,~~ in the x-y coordinate as shown in Figure 2, n is the refractive index of the ultra-fine steering region 24, and $L(x)$ is the effective length of the fine-steering region 24 along x-axis, which is propagating direction within the ultra-fine steering region 24. The modulation of the refractive index n is a function of the electric field.

[0018] As shown in Figure 2, the nonlinear crystal bulk material 20 is ~~countered~~ contoured to have several exterior planes, including an ~~incident plane~~ input face 201, a ~~grating plane~~ reflecting face 202, an ~~reflecting plane~~ output face 203 and ~~an emerging plane~~ a grating face 204. The

integrated optical parametric oscillator further comprises at least three coatings 31, 32 and 33, and a holographic grating 34 formed on ~~incident plane 201~~ an input face 31, the reflecting plane 202, ~~the emerging plane~~ the output face 203 and the ~~grating plane~~ surface 204, respectively. The coatings 31, 32 and 33 are designed to be ~~anti-reflected~~ anti-reflective for light waves with predetermined wavelengths and highly reflective for light waves with other predetermined wavelengths. In this embodiment, a Nd:YAG laser pump source is selected to generate the pump ~~radiation~~ beam λ_p with the wavelength of about 1.064 microns, and the optical-parametric-oscillation region 22 is operative to convert the pump ~~radiation~~ beam λ_p into a signal ~~wave~~ beam λ_s at 1.54 microns and an idler ~~wave~~ beam λ_i at about 3.442 microns. The coating 31 is highly reflective to the signal and idler ~~waves~~ beams λ_s and λ_i and anti-reflective to the pump ~~radiation~~ beam λ_p. Therefore, almost 100% of the pump beam λ_p incident on the coating 31 will transmit through the coating 31, while most of the signal and idler beams λ_s and λ_i will be reflected thereby. The coating 32 is highly reflective to the pump ~~radiation~~ beam λ_p and the idler ~~wave~~ beam λ_i and ~~is anti-reflective to~~ the signal ~~wave~~ beam λ_s. The coating 33 is highly reflective to all of the pump source λ_p~~, the signal wave λ_s~~ and the idler ~~wave~~ beam λ_i, and is partially transmittive to the signal beam λ_s. When a light is incident onto the holographic grating 34, depending on the incident angle α, some of the incident light is diffracted ~~and dispersed~~, and some of the incident light is reflected. ~~Therefore, almost 100% of the pump radiation λ_p incident on the coating 31 will transmit through the coating 31, while most of the signal and idler waves λ_s and λ_i will be reflected thereby.~~ The signal ~~wave~~ beam λ_s ~~will transmit through the coating 32, while~~ the pump ~~radiation~~ beam λ_p and the idler ~~wave~~ beam λ_i will be reflected ~~thereby~~ by the coating 32 on the reflecting plane 202. Regarding the coating 33, ~~all of~~ both the pump ~~radiation~~ beam λ_p~~, the signal wave λ_s~~ and the idler ~~wave~~ beam λ_i will be reflected thereby, and the signal beam λ_s will be partially reflected thereby. As all of the coatings 31, 32 and 33 are highly reflective to the idler ~~wave~~ beam λ_i, the idler ~~wave~~ beam λ_i will thus be resonated within the nonlinear optical bulk material 20. It will be appreciated that by adjusting the reflective characteristics of the coatings 31, 32 and 33, ~~different wave,~~ for example, the signal ~~wave~~ beam λ_s ~~will~~ could be resonated within the nonlinear optical bulk material 20, while the idler ~~wave~~ beam λ_i ~~can~~ could be coupled out. Alternatively, one can also design a degenerative or doubly-resonant optical parametric oscillator by adjusting the reflective characteristics of the coatings 31, 32, 33 and the grating 34.

[0019] Figure 3 shows the optical paths of the pump ~~radiation~~ beam λ_p, the signal ~~wave~~ beam λ_s and the idler ~~wave~~ beam λ_i. As shown in Figures 2 and 3, the optical-parametric-oscillation region 22 is located immediately ~~in front of the incident plane~~ adjacent to the input face 201 along the optical path of the pump ~~radiation~~ beam, such that after transmitting through the coating 31, the pump ~~radiation~~ beam λ_p is converted into the signal ~~wave~~ beam λ_s at 1.54 microns and the idler ~~wave~~ beam λ_i at 3.442 microns. The reflective characteristics of the coating 31 ensure that the pump ~~radiation~~ beam λ_p is the only input ~~of~~ to the integrated optical parametric oscillator. On the other hand, in the situation that the signal and idler ~~waves~~ beam λ_s and λ_i generated by the optical-parametric-oscillation region 22 are reflected back to the coating 31, the high reflectance of the coating 31 to the signal and idler beams will then reflect these waves back to the nonlinear optical bulk material 20. Therefore, the loss due to reflection or other optical effect can be minimized.

[0020] The signal ~~wave~~ beam λ_s and the idler ~~wave~~ beam λ_i are then incident on the holographic grating 34. In other words, the optical parametric oscillation region 22 is located between the ~~incident plane~~ input face 201 and the grating ~~plane~~ 204 along optical path of the pump ~~radiation~~ beam λ_p as well as the signal and idler ~~waves~~ beam λ_s and λ_i. As known in the art, when a light is incident on the holographic grating 34, some of the light is specularly reflected thereby, while some of the light is diffracted thereby ~~will be separated (dispersed) into its constituent monochromatic components. The component dispersed by the grating depends on the incident angle of the light as:~~ according to the grating equation as follows:

$$m\lambda = d(\sin\alpha + \sin\beta) \qquad (4),$$

where m is the diffraction order, d is the groove spacing of the grating 34, α is the incident angle to the grating 34, and β is the diffraction angle by the grating 34. ~~Therefore~~ In the present invention, by adjusting the ~~incident~~ diffraction angle ~~α~~ β, ~~both~~ the signal ~~wave~~ beam λ_s ~~and idler λ_i~~ can be tuned with desired wavelengths. The holographic grating 34 used in this embodiment has 200 to 500 grooves per millimeter, for example. In this embodiment, as the holographic grating 34 is permanently attached to or integrated on the grating ~~plane 304~~204, the adjustment of the diffraction angle β ~~upon the incident angle α~~ of the incident light ~~(both the signal and idler waves λ_s and λ_i)~~ cannot be achieved by mechanically re-orienting the holographic grating 34. In addition to the pre-designed geometry of the nonlinear optical bulk material 20, a ~~raw~~ fine adjustment of the ~~incident~~ diffraction angle ~~α~~ β is achieved by ~~adjusting the incident angle of the~~

~~pump source λ_p onto the incident plane 201~~ modulating the ultra-fine steering region 26. ~~In this embodiment, the raw adjustment is performed allowing a portion of the incident light (the signal and idler waves λ_s and λ_i) reflected by the holographic grating 34 towards the reflecting plane 202, and the other portion of the incident light diffracted by the holographic grating 34 towards the emerging plane 203.~~

[0021] In this embodiment, the coating 33 is designed to be ~~anti-reflective~~ partially transmissive at 1.54 microns and highly reflective at 3.442 microns; and therefore, the portion of the signal ~~wave~~ beam λ_s~~'~~ ~~diffracted~~ reflected by the holographic grating 34 partially transmits through the coating 33. It is appreciated that as the signal ~~wave~~ beam λ_s~~'~~ has been diffracted ~~and dispersed~~ by the holographic grating 34, the wavelength of the output wave ~~may deviate from~~ will be slightly tuned around 1.54 microns. Meanwhile, ~~and~~ the idler λ_i' ~~diffracted~~ reflected by the grating 34 is reflected by the coating 33 back towards ~~either the coating 31 or~~ the grating 34 ~~and reflected towards the coating 32~~. As all of the coatings 31, 32 and 33 and the holographic grating 34 are highly reflective at the wavelength of the idler ~~wave~~ beam λ_i ~~(λ_i')~~, the idler ~~wave~~ beam λ_i is resonating within the nonlinear optical bulk material 20.

[0022] While the portion of the signal ~~wave~~ beam λ_s~~'~~ diffracted by the holographic grating 34 emerges from the ~~emerging plane~~ output face 203 as the output wave, the other portion of the signal ~~wave~~ beam λ_s~~''~~ ~~reflected~~ diffracted by the holographic grating 34 propagates through the ultra-fine steering region 24 towards the coating 32. The signal ~~wave~~ beam λ_s~~''~~ is then reflected by the coating 32 back through the ultra-fine steering region 24, and is incident on the holographic grating 34 again. As mentioned above, by applying an electric field across the steering region 24, ~~the optical path of~~ the signal ~~wave~~ beam λ_s~~''~~ is ~~deviated~~ steered. One can control the electric field to ~~induce~~ adjust the optical path difference when the signal ~~wave~~ beam λ_s~~''~~ is propagating from the holographic grating 34 to the coating 32, and/or when the signal ~~wave~~ beam λ_s~~''~~ is propagating from the coating 32 to the holographic grating 34. ~~Thereby, being~~ Being reflected by the coating 32, the modulated signal ~~wave~~ beam $\lambda_{\cancel{m}\ s}$ is incident onto the holographic grating 34 with a ~~different incident angle α'~~ precisely selected angle β. ~~In~~ As shown in Figure 3, ~~the dashed line showing the optical path of~~ various wavelength components of the signal ~~wave~~ beam λ_s~~'' reflected from the reflecting plane 202 to~~ are diffracted by the grating ~~plane 204 without being modulated~~ 34 to propagate through the ultra-fine steering region 26 towards the reflecting plane 302. ~~As a result, the signal wave λ_m is diffracted with a desired~~

~~wavelength. The diffracted signal wave λ_m is then emerging from the emerging plane 203 as the output of the integrated optical parametric oscillator. In this embodiment, the signal wave λ_s" propagating through the steering region is steered with an angle of about ±1°. Such fine steering results in a fine adjustment of the wavelength tuning in nanometers.~~ It is known that only the normal incident wavelength component will be reflected by the coating 32 along the same optical path back towards the grating 34. By adjusting the voltage V applied to the ultra-fine steering region 24, a selected component of the signal beam λ_s will be steered with a normal incident angle upon the reflecting plane 202 as indicated by the dashed line in Figure 3. Thereby, the selected wavelength component of the signal beam λ_s can be collected at the output face 203. When the component with another wavelength is required, the voltage applied to the ultra-fine steering region 24 is adjusted to a different value, such that such wavelength component can be collected at the output face 203. Therefore, the tunability of the signal wave λ_s is obtained. Preferably, the steering angle of the wavelength components generated by the ultra-fine steering region 24 is about ±0.1°.

[0023] This disclosure provides exemplary embodiments of an integrated optical parametric oscillator. The scope of this disclosure is not limited by these exemplary embodiments. Numerous variations, whether explicitly provided for by the specification or implied by the specification, such as variations in shape, structure, dimension, type of material or manufacturing process may be implemented by one of skill in the art in view of this disclosure.

WHAT IS CLAIMED IS:

1. An integrated optical parametric oscillator ~~for converting a pump radiation into a signal wave and an idler wave and fine tuning the signal wave, comprising~~:

~~an incident plane being anti-reflective to the pump radiation and reflective to the signal wave and the idler wave;~~

an input face being anti-reflective to an incident pump beam;

an optical-parametric-oscillation region ~~in front of the incident plane~~ along an optical path of the pump ~~radiation~~ beam, the optical- parametric-oscillation region being operative to convert the pump ~~radiation~~ beam into ~~the~~ a signal ~~wave~~ beam and ~~the~~ an idler wave beam, wherein the input face is reflective to the signal beam and the idler beam;

a grating along an optical path of the signal beam and the idler beam converted by the optical-parametric-oscillation region, the grating being operative to diffract at least a portion of the signal beam;

a ~~grating~~ reflecting plane ~~in front of the optical parametric oscillation region~~ positioned along optical paths of the signal ~~wave~~ beam ~~and the idler wave, the grating plane being operative to diffract a portion of the signal and idler waves and reflect the other portion of the signal and idler waves~~ diffracted by the grating, wherein the reflecting plane is reflective to the signal beam;

~~an emerging plane, being anti-reflective to the signal wave and reflective to the pump radiation and the idler wave, the second coating being located along the optical path of the signal and idler waves diffracted by the grating plane;~~

~~a reflecting plane, being reflective to the pump radiation, the signal wave and the idler wave, the reflecting plane being located along the optical paths of the other portion of the signal and idler waves reflected from the grating plane; and~~

an ultra-fine-steering region between the reflecting plane and the grating ~~plane~~, the ultra-fine-steering region being operative to ~~change~~ steer the optical path of the signal ~~wave~~ beam ~~incident onto~~ diffracted from the grating ~~plane.~~; and

an output face along an optical path of the signal beam reflected from the grating, the output face being reflective to the pump beam and the idler beam and partially transmissive to the signal beam.

2. The integrated optical parametric oscillator of Claim 1, wherein the ultra-fine-steering region is operative to select a narrow line of the signal beam by steering the optical path of the signal beam diffracted from the grating.

~~2.~~ 3. The integrated optical parametric oscillator of Claim 1, wherein the ~~incident plane~~ input face, the optical-parametric-oscillation region, the grating ~~plane~~, the ~~emerging plane~~ output face, the reflecting plane and the fine-steering region are integrated on a single slab of a nonlinear optical bulk material.

~~3.~~ 4. The integrated optical parametric oscillator of Claim ~~2~~ 3, wherein the nonlinear optical bulk material includes a lithium niobate material.

~~4.~~ 5. The integrated optical parametric oscillator of Claim ~~2~~ 3, wherein the optical-parametric-oscillation region includes a part of the nonlinear optical bulk material being periodically poled.

~~5.~~ 6. The integrated optical parametric oscillator of Claim ~~2~~ 3, wherein the fine-steering region includes a part of the nonlinear optical bulk material and a ~~pair~~ pattern of electrodes deposited on two opposing surfaces of thereof.

~~6.~~ 7. The integrated optical parametric oscillator of Claim ~~2~~ 3, wherein the fine-steering region includes a part of the nonlinear optical bulk material subjected to an electric field.

~~7.~~ 8. The integrated optical parametric oscillator of Claim 1, wherein the pump ~~radiation~~ beam has a wavelength of about 1.064 micrometers, the signal ~~wave~~ beam has a wavelength of about 1.54 micrometers, and the idler ~~wave~~ beam has a wavelength of about 3.442 micrometers.

~~8.~~ 9. The integrated optical parametric oscillator of Claim 1, wherein the pump ~~radiation~~ beam has a wavelength of about 1.064 micrometers, the idler ~~wave~~ beam has a wavelength of about 1.54 micrometers, and the signal ~~wave~~ beam has a wavelength of about 3.442 micrometers.

~~9.~~ 10. The integrated optical parametric oscillator of Claim 1, wherein the grating ~~plane~~ includes a holographic grating with about 200 grooves/mm to about 500 grooves/mm.

~~10.~~ 11. An integrated optical parametric oscillator, comprising a nonlinear optical bulk material~~,~~ in which includes a locally periodically-poled region and a fine-steering region subjected to an electric field are formed.

12. The integrated optical parametric oscillator of Claim 11, further comprising a grating between the locally periodically poled region and the steering region to diffract an optical signal into various wavelength components towards the fine-steering region.

13. The integrated optical parametric oscillator of Claim 12, wherein the fine steering region is operative to steer a selected one of the wavelength components with a predetermined angle.

14. The integrated optical parametric oscillator of Claim 11, further comprising a reflecting plane to reflect the steered wavelength component back to the grating.

~~11.~~ 15. The integrated optical parametric oscillator of Claim ~~10~~ 11, wherein the nonlinear optical bulk material includes a lithium niobate.

~~12.~~ 16. The integrated optical parametric oscillator of Claim 10 11, wherein the locally periodically-poled region has a length of about 30 mm.

~~13.~~ 17. The integrated optical parametric oscillator of Claim ~~10~~ 11, wherein the nonlinear optical bulk material further comprises a plurality of exterior coated planes forming a resonator of a wave at predetermined wavelengths.

~~14.~~ 18. A tunable, narrow-line laser system, comprising:

a pump ~~radiation~~ beam source, operative to generate a pump radiation beam;

an integrated optical parametric oscillator, including a nonlinear optical bulk crystal, which further comprises:

an ~~incident plane~~ input face of the pump ~~radiation~~ beam;

an optical-parametric-oscillation region converting the pump ~~radiation~~ beam into a signal ~~wave~~ beam and an idler ~~wave~~ beam;

a grating ~~plane,~~ reflecting a portion of the signal and idler ~~waves~~ beam and diffracting the other portion of the signal ~~wave~~ beam and the idler ~~wave~~ beam;

an ~~emerging plane, emerging the other~~ output face, coupling out the portion of the signal ~~wave diffracted~~ beam reflected from the grating ~~plane~~ and reflecting the ~~other~~ portion of the idler ~~wave diffracted~~ beam reflected from the grating ~~plane~~;

a reflecting plane, reflecting the portion of the signal and idler ~~waves~~ beams ~~reflected~~ diffracted from the grating ~~plane~~; and

a fine-steering region between the grating ~~plane~~ and the reflecting plane for generating an optical path difference of the other portion of the signal and idler ~~waves~~ beams reflected from reflecting plane and incident on the grating ~~plane~~.

~~15.~~ 19. The tunable, narrow-line laser system of Claim ~~14~~ 18, wherein the pump ~~radiation~~ beam source includes a Nd:YAG laser.

~~16.~~ 20. The tunable, narrow-line laser system of Claim ~~14~~ 18, wherein the nonlinear optical bulk crystal includes a lithium niobate crystal.

~~17.~~ 21. The tunable, narrow-line laser system of Claim ~~14~~ 18, wherein the optical-parametric-oscillation region includes a periodically-poled region of the nonlinear optical bulk crystal.

~~18.~~ 22. The tunable, narrow-line laser system of Claim ~~14~~ 18, wherein the optical-oscillation-region has a length of about 30 mm.

~~19.~~ 23. The tunable, narrow-line laser system of Claim ~~14~~ 18, wherein the optical-parametric-oscillation region being operative to convert the pump ~~radiation~~ beam into the signal ~~wave~~ beam with a wavelength of about 1.54 μm and the idler ~~wave~~ beam with a wavelength of about 3.442 μm.

~~20.~~ 24. The tunable, narrow-line laser system of Claim ~~14~~ 18, wherein the optical-parametric-oscillation region being operative to convert the pump ~~radiation~~ beam into the signal ~~wave~~ beam with a wavelength of about 3.442 μm and the idler ~~wave~~ beam with a wavelength of about 1.54 μm.

~~21.~~ 25. The tunable, narrow-line laser system of Claim ~~14~~ 18, wherein the fine-steering region includes a region of the nonlinear optical bulk crystal subjected to an electric field.

~~22.~~ 26. The tunable, narrow-line laser system of Claim ~~14~~ 18, wherein the ~~incident plane~~ input face, the grating ~~plane~~, ~~emerging plane~~ output face, and the reflecting plane are all reflective to the idler ~~wave~~ beam and arranged as a resonator of the idler ~~wave~~ beam.

ABSTRACT OF THE INVENTION

An integrated optical parametric oscillator, having an optical parametric oscillation region to convert a pump source into a signal ~~wave~~ beam and an idler ~~wave~~ beam, and a fine-steering region to change optical path of the signal ~~wave~~ beam. The optical parametric oscillator is contoured with a plurality of exterior planes with specific reflective characteristics to form a resonator of the idler ~~wave~~ beam while ~~directing~~ reflecting and diffracting the signal ~~wave~~ beam with a desired wavelength.

t:\client documents\norte\513a\substitute app with markings.doc
Jessie